[redacted]

R55-44

[Reprinted from FOOD RESEARCH, 1955, Vol. 20, No. 5, Pages 399-414]

HEAT PROCESSING OF BEEF. V. TEMPERATURE DISTRIBUTION PATTERNS DURING PROCESSING OF BEEF AT HIGH RETORT TEMPERATURES[a]

H. HURWICZ[b]
The Trane Company, La Crosse, Wisconsin
AND
R. G. TISCHER[b]
The Quartermaster Food and Container Institute for the Armed Forces, Chicago, Illinois

The modern trend in evaluation of lethality of canning processes *(1, 2, 8)* is founded on the basis of thermal history of the whole can volume rather than on that of the geometrical center of the container only, and necessitates a study of temperature distribution in the container during the canning process. With the exception of the paper by Hurwicz and Tischer *(5)*, no such data pertaining to the foodstuffs are available in the literature.

The experimental temperature distributions and their analyses presented here are a part of a larger study to determine thermal, thermobacteriological, and other physical characteristics of round of beef processed at higher than conventional retort temperatures and for short processing times. The containers used were 300 x 308 cans, retort temperature range was 225-315°F. The experimental procedure was similar to that used by Hurwicz and Tischer in Part II of this series *(5)* and has been fully described in *(3)* and *(6)*.

The objective of this work was to determine the temperature distributions in the can during processing and to analyze the experimental deviations from the theoretical expectations.

EXPERIMENTAL TEMPERATURE DISTRIBUTION

The temperature distributions observed and mapped during this experiment did not meet the theoretical expectations. The expected isothermal distribution for a homogeneous isotropic body heating by conduction would be symmetrical about the vertical and horizontal axes; it would change from a cylindrical distribution on the outside of the can through an ellipsoidal form to end in a point at the center of the container or, all these forms would be taken by one isothermal surface moving from the outside toward the center of the container as the heating progressed in time. Approximately such a distribution was observed by Hurwicz and Tischer *(5)* in No. 2 cans of beef, even though some of the constants of the heating equations had to be multiplied by a correction factor applied to all locations in the container.

Mapping procedure. The locations investigated have been shown in Figure 1, and have been assumed to be located on any half-plane of the central vertical cross-section. The diagrams of the isotherms were prepared in two steps. First, 72 interpolation diagrams were prepared for each cut of round (e.g. Fig. 2). For this purpose temperatures obtained from 3 heating curves were plotted against the points located along one of the 4 vertical axes in the can. Five-minute intervals were used from the beginning to the end of the heating phase for each retort temperature (RT). Next, the temperatures were determined from the interpolation diagram (for heating periods increasing in length by 5-minute intervals) at the intersection of the horizontal tem-

[a] Journal Paper J-2745 of the Iowa Agricultural Experiment Station, Ames, Iowa. Project 1123.

[b] Formerly of Iowa State College, Ames, Iowa.

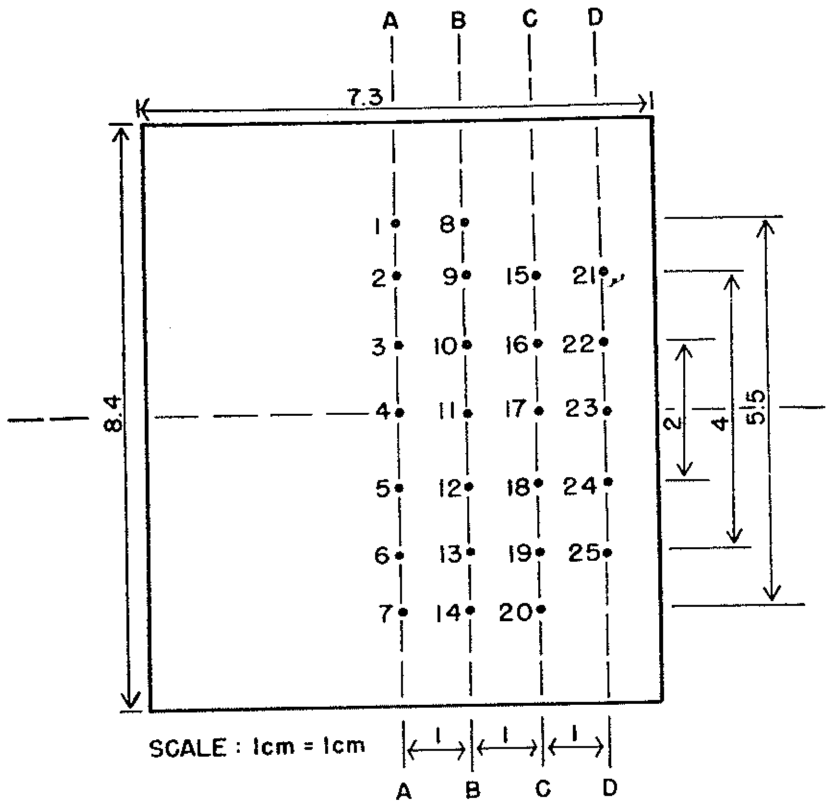

Figure 1. Distribution of locations tested during the investigation. (Vertical cross-section through the central axis of 300 x 308 cans)

perature line with the appropriate equal-time (isochronal) line. The intersection of these 2 lines defined in the space the location in the container. This procedure was repeated 4 times (once for each vertical axis: A-A, B-B, C-C, and D-D) and usually yielded 8 locations in the container at the same temperature for the heating period. The points thus located in the can were connected by an isothermal line on a diagram representing the central vertical cross-section of the can. Figures 3, 4, and 5 represent typical isothermal temperature distributions observed in the course of this experiment from 1512 heating curves at 25 locations in a 300 x 308 can of beef for 6 retort temperatures.

Occurrence of distorted temperature distribution. The isothermal temperature distributions exhibited considerable deviations from theoretical expectations. Considering the distribution of a number of isothermal lines after some time elapsed from the beginning of heating, one notices that the point of greatest heating lag[c] did not coincide with the geometric center of the can. The point of greatest heating lag in almost all of the derived distributions was found to be displaced from the center and located in the central horizontal cross-section of the can. Sometimes it was located below or above this plane.

The form of isothermals located in the outside region of the can did not depart from the theoretically expected, but the isothermals found in the central region instead

[c] This point has been commonly called "the point of slowest heating" which erroneously implies lower thermal diffusivity at this location; "the point of greatest heating lag" implies correctly the highest temperature difference at time zero on the assymptote of the heating curve.

of being ellipsoidal displayed cardioid characteristics. In the vicinity of the center, the theoretically concentric elipsoidal or spherical shells were replaced by doughnut-shaped volumes (considering the revolution of the vertical cross-section by 360° about the central axis), similar to those shown in Figures 6 and 7. The distributions appeared to be symmetric about the central horizontal plane. The same effects were observed when the changes in the space of one isothermal surface were traced at different intervals of time. These phenomena appeared to be more pronounced for high retort temperatures in the range from 279-315°F.

The area of greatest heating lag was removed further from the central axis and the isothermals assumed cardioid shape closer to the boundaries of the container.

The effect of longer heating periods on the temperature distributions was similar to the effect of higher retort temperature.

In view of the fact that these phenomena were observed at all temperatures and times, and for all of the 3 cuts of round (separately as well as for the average of all three), it seems improbable that this occurrence was only a chance event or due to the interpolation procedure. The proof of the reality of this occurrence will be given in the evaluation of the parameters of the heating equations in the following section. Meanwhile, an explanation of the mechanism of the occurrence of the distorted temperature distributions and departure from theoretical expectations will be attempted.

Mechanism of occurrence of distorted temperature distribution. Temperature distributions expected from theoretical consideration obey the law expressed in the heat conduction equation *(4)* given in Table 1. This equation holds for a homogeneous

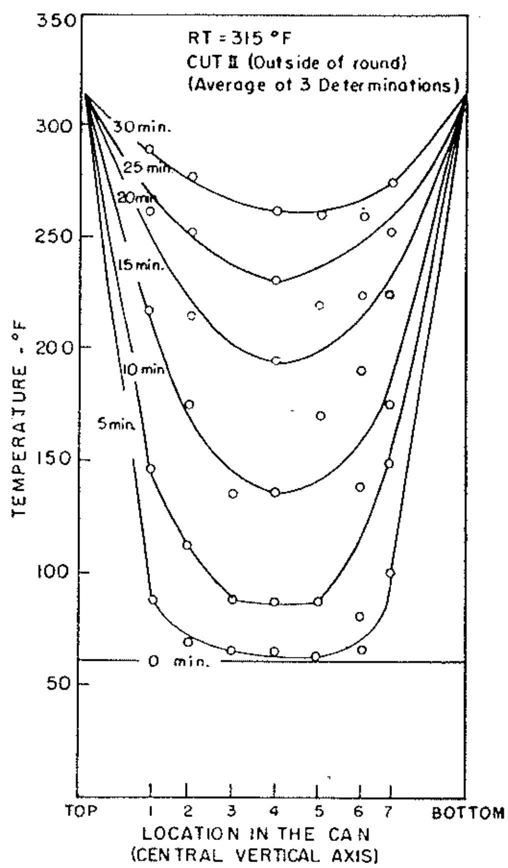

Figure 2. Interpolation diagram for temperature distribution determination. (Isochronal temperature distribution)

TABLE 1

Distribution of theoretical intercept coefficients (a_{11})[1] of heat conduction equation, and values of can constants for 300 x 308 can

$\pm z^2$ (cm.)	r (cm.)[3]			
	0	1	2	3
0.00	2.041	1.986	1.825	1.572
1.00	1.900	1.849	1.699	1.404
2.00	1.495	1.455	1.337	1.152
2.75	1.054	1.026	0.9426	....

$\mu_1 = 0.3294$ $\lambda_1 = 0.3740$ $(\mu_1^2 + \lambda_1^2) = 0.2484$

[1] $RT - CT = (RT - IT)\, A_{11}\, J_0(\mu_1 r) \sin \lambda_1 (z + 1)\, e^{-k(\mu_1^2+\lambda_1^2)t} = a_{11}\, e^{-k(\mu_1^2+\lambda_1^2)t}$.
[2] Distance from the central horizontal cross-section.
[3] Distancee from the central vertical cross-section.

isotropic body, and the solution includes constants depending on the initial uniform temperature distribution. A departure from any of these assumptions will result in departure from the theoretical expectation. The material tested in this investigation

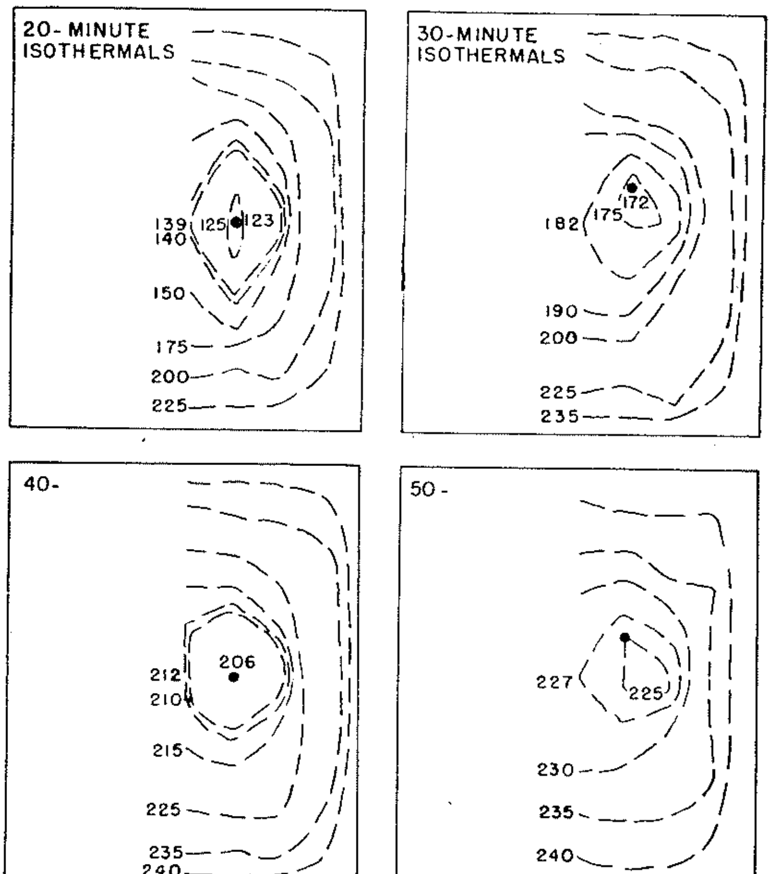

Figure 3. Isothermal temperature distributions after four intervals of time during heating at 243°F.

(Cut III—inside of the round)

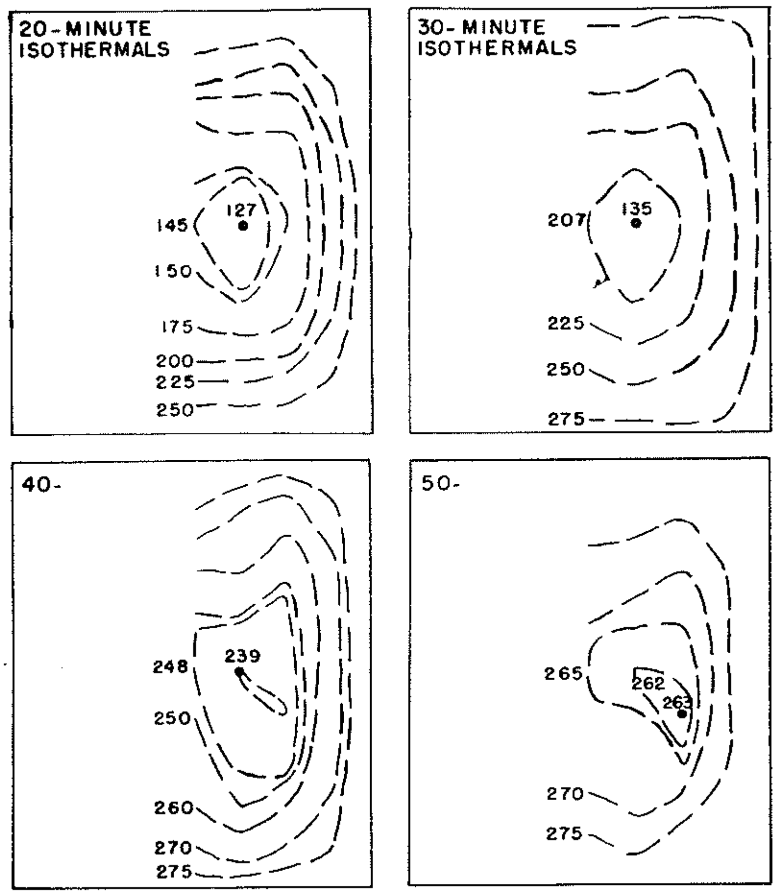

Figure 4. Isothermal temperature distributions after four intervals of time during heating at 279°F.

(Cut III—inside of the round)

(beef) is neither homogeneous nor isotropic; furthermore, its structure undergoes changes in chemical composition and moisture content during the process.

The anisotropy of the piece of beef sealed in the container with the fibers parallel to the vertical axis is evident. If the resistance to the heat flow is lower along the fibers than across them, then the heat wave front may be expected to progress faster towards the center from the bottom and from the top of the cylinder than from the sides. As a result, the two isothermal fronts, one concave upward and the other downward, meet at the center before the ''side'' isothermals can reach this point, and a volume of greatest heating lag of doughnut shape (torus) is formed. Figures 6 and 7 picture such occurrence. This phenomenon, which may be called an ''end effect'' will be more pronounced in cylinders which have a height-diameter ratio (l/a) of unity or less. This may explain the non-occurrence of this phenomenon in a previous experiment with No. 2 cans *(5)*.

The cardioid shape of the isothermals may be explained in the same manner by the relative velocities of the moving heat fronts and their concavities. The effect of the inherent anisotropy of beef is further accentuated by the searing effect on the sides of the cylinder of beef processed at higher temperatures; this effect constitutes a type of ''casehardening'' and may contribute to higher resistivity of the sides of the cylinder of meat which would retard the movement of the isothermals. The "case-hardening" effect which was apparent for even the shortest processing times from the very beginning of the process may be stronger along the sides of the cylinder because a whole length of the fiber would be sealed, whereas at the top and bottom of the can only the fiber ends would be sealed and free passage for heat would be left between them. A higher resistance to heat flow across the fibers would be expected because of the resistivity of connective tissue running parallel to the fibers and because of less resistance to heat flow in the straight vertical pass, compared to sine path of flow perpendicular to the fiber. All these characteristics of beef may result in a formation of several effective centers of heating (points of greatest heating lag) other than the geometric center. These effective centers are located in a circumference in the horizontal cross-section of the can and may necessitate a change in the parameters of the heat conduction equation for this case.

The change, if any, in thermal diffusivity value from the center to the outside of the can, due to changes in chemical composition and moisture content, might be an additional factor in distortion of the temperature distribution. This has not been observed, however, during this experiment, as diffusivities were found to be independent of the location in the can.

Calculated distribution of parameters of the heating curves. *Intercept Coefficient—$\hat{a}_{11}$*: The theoretical distribution of intercept coefficients $\hat{a}_{11}$ defined in Table 1

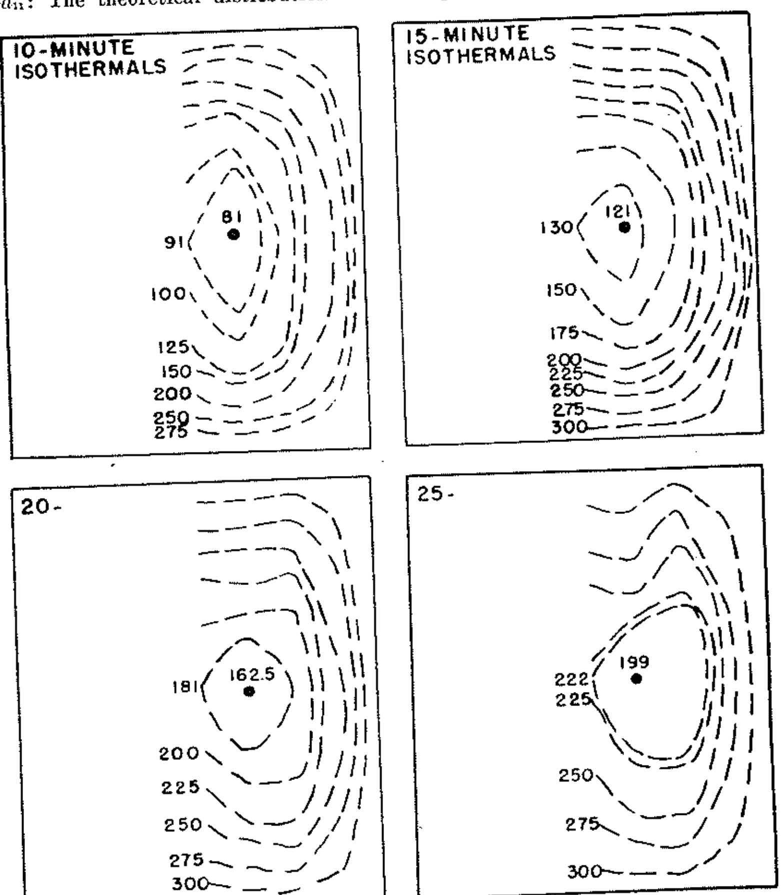

Figure 5. Isothermal temperature distributions after four intervals of time during heating at 315°F.

(Cut III—inside of the round)

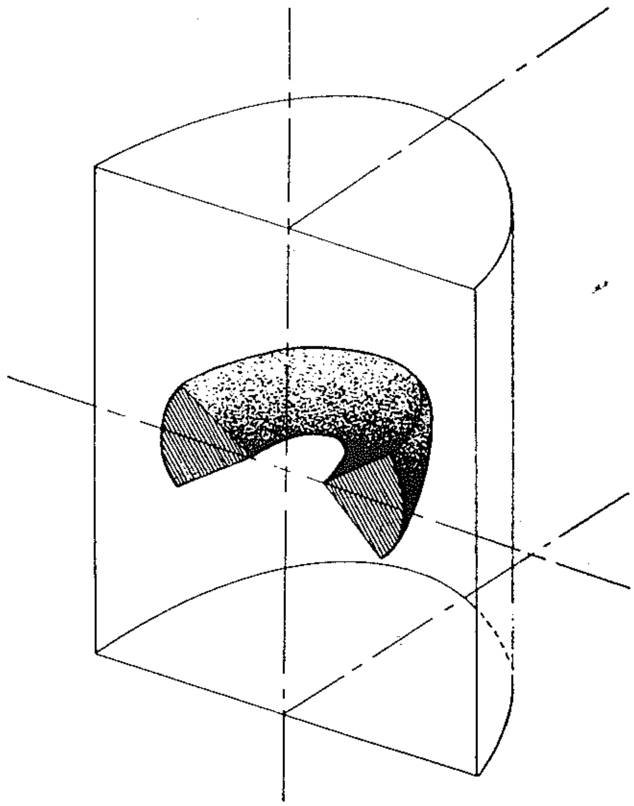

Figure 6. Triangular torus of lowest temperatures in a cylindrical can (300 x 308).

(on the assumption of uniform initial temperature distribution) indicates the greatest lag and subsequently lowest temperatures at any time of processing at the center of the container. These coefficients have the higher value at the center of the container and decrease toward the outside. The coefficients in a relationship corrected for average experimental conditions by a factor of f_s would display the same trend *(5)*. If the estimates available for the coefficients actually determined during an experiment on the basis of temperature and time measurement have a different distribution, the location where they have the highest value (experimental error taken into account) will be the location of greatest lag in heating and as such will display lowest temperatures at any time of processing. This will be true if diffusivities are the same for the whole can. Whatever the cause of the initial lag, the effects on distribution of the intercept coefficients will be as above and thus confirm the reality of distribution of temperatures mapped from experimental heating curves.

Since every measurement is subject to an experimental error the actual position of two isothermal lines relative to each other is not certain. It may be said that e.g. on Figure 4 the 20-minute isothermals are in effect 20 minutes $\pm$ 1 sec. isothermals; also, that the 145°F. and 150°F. isothermals are 145 $\pm$ 5° and 150 $\pm$ 5° isothermals. The problem is then to define in the space of the container and in the time the volume shell corresponding to the fiducial limits of the error; this in effect leads to a 5-dimensional space (X, Y, Z space coordinates and t-time and T-temperature) analysis, very difficult if at all possible to make on the basis of temperature readings. Instead, comparisons of intercept coefficients (functions of temperature, time and space coordinates) are made to ascertain statistically whether or not differences between them are real (significant). This together with actual values of the coefficients fixes their distribution as well as the distribution of temperatures. In this manner one is able to say whether

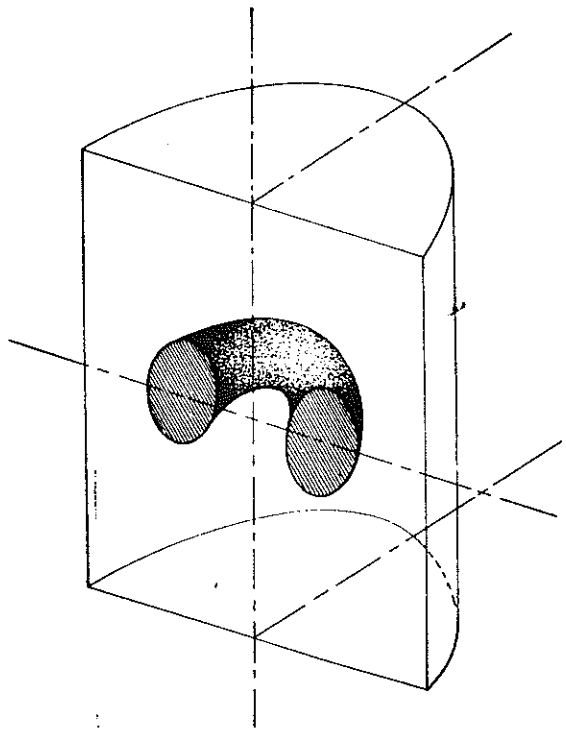

Figure 7. Circular torus of lowest temperatures in a cylindrical can (300 x 308).

the distortion of temperature is real or due to the experimental error. The value of this type of analysis will be demonstrated below where apparent shift of the point of greatest heating lag in the vertical direction indicated by experimental temperature distribution has been disproved by statistical analysis of intercept coefficients, and must be ascribed to experimental variation.

The values of intercept coefficients are based on regression calculations and as such have smaller experimental error than individual temperature readings. They reduce the infinite number of temperature distribution diagrams, which would be necessary to cover one process, to one coefficient distribution indicative of the whole process. Since they are determined from regression, the estimates of the experimental error are readily available for calculation of fiducial units and statistical comparisons. The conclusions based on coefficient distribution must be considered valid for temperature distributions since the coefficients are functions of the temperature and time, and as such offer proof of reality or nonreality of observed phenomena.

Lag Coefficient—C_1: The relative departure from the theoretically expected constants may be measured in terms of the ratio $C_1 = \hat{a}_{11}/a_{11}$ referred to henceforth as the lag coefficient, where $\hat{a}_{11}$ is determined from regression equations and a_{11} is the theoretically expected value. If the lag coefficient is smaller than unity it indicates a smaller actual lag than in the ideal case. The magnitude of this coefficient for various locations in the can will indicate the comparative (relative) departure (or deviation) from the theoretical relationship at these locations. The relatively lower values of the lag coefficient at some locations compared to others will then indicate a decrease in heating lag of larger order, compared to the theoretical, than for the other locations. Values smaller than unity compared to values larger than unity immediately indicate that temperatures respectively higher and lower than the theoretical temperatures have to be expected at any time of processing at these locations.

The use of the lag coefficient in interpretation of the data permits rapid comparison of experimental results with theoretical expectations or of conversion of theoretical temperature distributions to experimental ones if the data on $\hat{a}_{11}$ and a_{11} are available.

The interpretation may be further facilitated if an average lag coefficient is calculated which amounts to an average correction factor for the heating relationship with respect to the whole space in the container and accounts for the effect of fitting of one term of the heating equation. The average temperature distribution may then be visualized with the lowest values again at the center and with the isothermal lines of similar shape to the theoretical ones but displaced with respect to them.

The average lag coefficient now assumes the place of unity in the comparison with theoretical distribution and less than average values indicate smaller lag, or higher temperatures at the location investigated, while values higher than the average indicate greater lag or lower temperature than predicted from the average relationship.

Cardioid Distribution: Assume now that at a given location the temperature is higher than the predicted one, this indicates that the lower temperature isothermal moved closer (smaller lag) to the center of the can for the time considered; for a lower actual temperature, the opposite is true and the isothermal considered is removed farther from the center. The values of assumed lag coefficients illustrate this phenomenon in Figure 8. Such an occurrence may well result in the distortion of an ellipsoidal isothermal into a cardioid one as is shown in Figure 8 for a hypothetical condition. Ultimately this results in an area of lowest temperatures off the central vertical axis as shown in Figures 6 and 7. This schematic presentation is one of many possible combinations depending on variables encountered during a thermal process.

Analysis of actual mechanism of heat penetration into a container. A separate problem is presented in attempts at determination of the causative agents behind the departure from theory other than an average correction in the theoretical relationship for the whole space of the can. In the previous discussion of the graphical representation of actual temperature distribution anisotropy, casehardening effect of chemical and

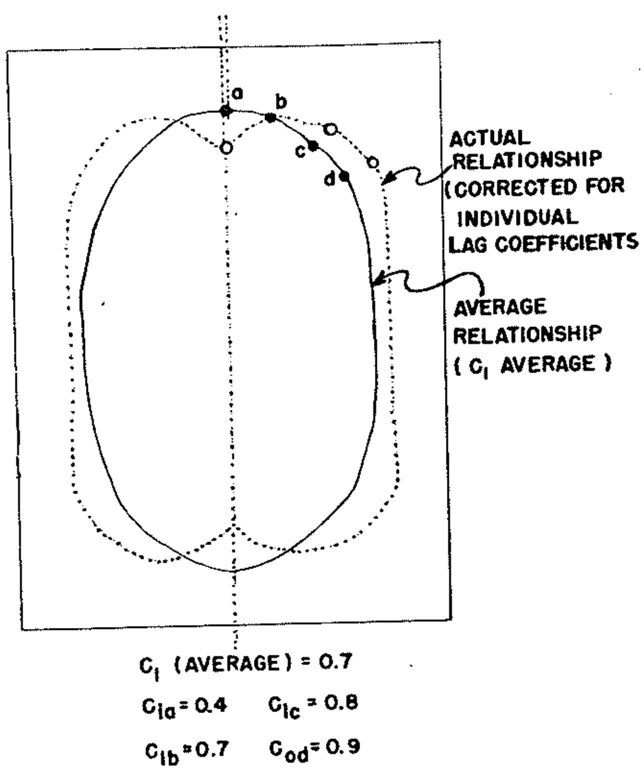

Figure 8. Hypothetical deviations from average heating equation resulting in cardioid temperature distribution.

moisture changes in meat were mentioned. In order to obtain a clearer picture of changes occurring in the container during processing, an analysis was made of the presumed actual mechanism of heat penetration compared to the ideal one. One of the causes of the actual mechanism of heat penetration being different from the ideal one is the presence of an initial temperature gradient increasing towards the peripheries of the container. Even if the uniform temperature distribution is maintained carefully before the can is put in the processing retort, the finite heating rate of the retort to the designated temperature creates a temperature gradient which causes an initial lag smaller than theoretically expected in the outside region of the can compared to the inside since obviously temperature on the periphery is higher than inside. Lengthwise, the gradient is smaller than along the horizontal plane since $(l/a) > 1$. Thus, this effect on the experimentally determined heating lag is more pronounced horizontally than vertically in terms of the computed $\hat{a}_{11}$. The decrease in the intercept coefficient is relatively larger for the outside vertical axes than for the central vertical axis.

The average initial temperature difference (RT-IT)av. is used in the determination of $\hat{a}_{11}$ from $\hat{a}_{11}$ (RT-IT)av. This procedure results in use of $\hat{a}_{11}$ which is overestimated for the center and underestimated for the outside. This effect of initial temperature gradient on computed values should be accounted for during interpretation of results based on $\hat{a}_{11}$ values. In other words the actual heating lag in the interior of the can is smaller than indicated by $\hat{a}_{11}$ and the reverse is true for the outside of the container. These effects are due solely to the existence of an initial non-uniform temperature distribution.

Due to fitting of only one term of the expansion of the conduction equation for heating curves, all $\hat{a}_{11}$ are uniformly decreased. This accentuates (in terms of per cent) the previous effects when lag coefficients are calculated. The effects of anisotropy and casehardening are more pronounced for high temperatures and stronger with time because the initial distribution patterns are more disturbed, and also because more isotherms penetrate into the can. This effect of anisotropy is expressed in higher resistance to radial flow than to axial flow, and counteracts the effects of non-uniform temperatures mostly along the central vertical axis and on the vertical boundaries of the can. It results in an increase of a_{11} on these latter boundaries and in decrease of a_{11} along the vertical axis. Thus for the outside boundaries it can be expressed as:

$$(a_{11}/f_s) - (\Delta_1 a_{11}) + (\Delta_2 a_{11}) = \hat{a}_{11} \qquad \text{Eq. 1a}$$

(one term fitting effect)	—	(non-uniform temp. effect)	+	(anisotropy effect)	=	(expected coefficient)

and along the vertical axis as:

$$(a_{11}/f_s) + (\Delta_1 a_{11})' - (\Delta_2 a_{11})' = \hat{a}_{11} \qquad \text{Eq. 1b}$$

The effects of departure from idealized conditions are much smaller in the intermediate space of the can because the average initial temperature used in calculations approximates the actual difference in this region. As a result, the intercept coefficients are less affected by all the factors mentioned and are more nearly equal to a_{11}/f_s or to a_{11} and thus may result in a greatest heating lag volume.

The relative magnitudes of the effects $\Delta_1 a_{11}$ (due to the departure from uniform initial temperature distribution and $\Delta_2 a_{11}$ (due to anisotropy) for both regions affect the ultimately determined $\hat{a}_{11}$ for these locations. If the anisotropic effect were considered separately, the expected lag coefficients C_i for the central vertical axis will be lowered much more than those for the outside (the effect of fitting of one term only of the equation being assumed the same throughout the can). If in addition the effect of the presence of the initial temperature gradient is accounted for, the outcome is not certain and depends on the relative magnitudes of $(\Delta_1 a_{11})'$ and $(\Delta_1 a_{11})$. The resulting lag coefficients now may be lowered more for the outside than inside as was observed in the course of this experiment, or may be the same.

For certain combinations of conditions, $\hat{a}_{11}$ may remain equal to a_{11}/f_s or even become equal to or greater than a_{11}. The occurrence of any of these events will depend upon the processing conditions, the size of the can and the initial temperature distribution within the can.

The assumption of 2-dimensional flow instead of the actual 3-dimensional flow could also affect the determination of intercept coefficients ($\hat{a}_{11}$). There is no way of evaluating this effect from the data collected during this investigation, although the exploration of it could prove to be of value.

RESULTS AND DISCUSSION

The values of the intercept coefficient ($\hat{a}_{11}$) anl lag coefficients ($C_1 = \hat{a}_{11}/a_{11}$) determined from the regression equations were evaluated in the search for confirmation of observed temperature distribution patterns. At the same time an attempt was made to test the applicability of the proposed analysis of mechanism of heat transfer in beef to the data obtained during the experiment, and to evaluate the relative contribution of the causative agents in distortion of theoretical temperature distributions as indicated by the determined intercept values.

a. Intercept coefficient—$\hat{a}_{11}$:

The distribution of $\hat{a}_{11}$ (Table 3) exhibited on the average the highest values for the can at locations 5, 10, 11, 12, and occasionally at locations 16, 17, and 18 (Fig. 1). The variance associated with location 5 (on the central vertical axis) was usually excessive and the student's "t"-test *(7)* did not indicate significant differences between the $\hat{a}_{11}$ values at the center and at location 5. A series of comparisons between the $\hat{a}_{11}$ value at

TABLE 2

Intercept coefficients ($\hat{a}_{11}$) for six retort temperatures determined by regression methods

Location	Retort temperature (°F.)						
	225	243	261	279	297	315	Average
1	0.732	0.907	0.829	1.560	1.575	4.091	1.619
7	0.805	0.759	1.209	0.974	1.005	1.256	1.001
8	1.008	1.235	1.320	1.564	1.101	1.552	1.297
14	0.373	1.409	1.572	1.095	1.300	1.232	1.134
20	0.735	1.145	1.670	1.523	1.106	1.594	1.296
21	0.767	0.821	0.814	0.816	1.110	1.352	0.947
22	0.454	0.997	1.056	1.130	1.229	0.917	0.964
23	0.810	1.032	1.087	0.964	1.167	0.855	0.986
24	0.611	0.903	1.165	1.059	1.322	0.855	0.986
25	0.697	0.643	0.554	0.937	1.351	0.663	0.608
2	1.069	1.334	1.622	1.348	2.241	1.541	1.526
6	0.902	1.533	1.673	1.473	1.310	1.324	1.339
9	1.075	1.401	1.886	1.613	1.708	2.141	1.637
13	1.618	1.890	1.923	1.355	2.390	1.600	1.798
15	0.775	1.442	1.605	1.294	1.112	1.209	1.240
16	1.346	2.082	1.658	1.601	1.241	1.211	1.524
17	1.267	1.363	2.230	2.109	1.521	1.261	1.625
18	1.438	1.592	1.859	1.434	1.336	1.260	1.487
19	1.288	2.123	1.456	1.449	1.231	1.304	1.475
3	1.380	1.355	1.729	1.620	1.465	1.085	1.439
4	1.463	1.3448	1.6295	1.4535	1.4453	1.2860	1.437
5	1.959	2.272	2.339	2.022	1.414	1.793	1.967
10	1.249	1.307	1.255	2.813	1.930	1.689	1.707
11	1.109	1.353	1.724	1.374	1.321	1.248	1.355
12	1.496	1.615	2.514	1.413	2.081	1.527	1.774

TABLE 3

Distribution of intercept coefficients ($\hat{a}_{11}$) in 300 x 308 can

r (cm.)	z (cm.)						
	2.75	2.00	1.00	0.00	−1.00	−2.00	−2.75
				RT = 225°F.			
0	0.732	1.069	1.380	1.464	1.959	0.902	0.805
1	1.008	1.075	1.249	1.109	1.496	1.618	0.373
2	......	0.775	1.348	1.267	1.438	1.288	0.735
3	......	0.767	0.454	0.810	0.611	0.697	......
				RT = 243°F.			
0	0.907	1.334	1.355	1.345	2.272	1.533	0.759
1	1.235	1.401	1.307	1.353	1.615	1.890	1.409
2	......	1.442	2.082	1.363	1.592	2.123	1.145
3	......	0.821	0.997	1.032	0.903	0.643	......
				RT = 261°F.			
0	0.829	1.622	1.729	1.629	2.339	1.673	1.209
1	1.320	1.886	1.255	1.724	2.514	1.923	1.572
2	......	1.605	1.658	2.230	1.859	1.456	1.670
3	......	0.814	1.056	1.087	1.165	0.554	......
				RT = 279°F.			
0	1.580	1.348	1.620	1.453	2.022	1.473	0.974
1	1.564	1.613	2.813	1.374	1.413	1.353	1.095
2	......	1.294	1.601	2.109	1.434	1.449	1.523
3	......	0.816	1.130	0.964	1.059	0.937	......
				RT = 297°F.			
0	1.575	2.241	1.465	1.445	1.414	1.310	1.005
1	1.101	1.708	1.930	1.321	2.081	2.390	1.300
2	......	1.112	1.241	1.521	1.336	1.231	1.106
3	......	1.110	1.229	1.167	1.322	1.351	......
				RT = 315°F.			
0	4.091	1.541	1.085	1.286	1.793	1.324	1.256
1	1.552	2.141	1.689	1.248	1.527	1.600	1.232
2	......	1.209	1.211	1.261	1.260	1.304	1.594
3	......	1.352	0.917	0.855	0.853	0.663	......

the center and the other locations with higher $\hat{a}_{11}$ values was made by means of "t"-tests of significance *(7)*. The "t" values calculated for the 1% probability level indicated the presence for every processing temperature of at least one location displaying greater heating lag than the center. Location 12 displayed heating lag greater than at the center for the retort temperatures of 243, 261, 297, and 315°F., location 5 for 225 and 279°F.; location 13 at 243 and 297°F.; and location 11 at 261 and 297°F.; location 10 at 315°F.; location 17 at 279°F.; and location 19 at 315°F. The above values are in good agreement with the temperature distributions shown on Figures 3, 4, and 5 and indicate a displacement of the location of greatest heating lag from the central vertical axis toward the outside of the container. This horizontal shift was found to be more pronounced for the middle of the temperature range used (225-315°F.) and did not confirm totally the tendency of the displacement to increase with the retort temperature.

TABLE 4
Lag coefficients ($C_1 = \hat{a}_{11}/a_{11}$) for six retort temperatures

Location	Retort temperature (°F.)						
	225	243	267	279	297	315	Average
1	0.694	0.881	0.787	1.499	1.494	3.881	1.536
7	0.764	0.720	1.147	0.924	9.954	1.192	0.950
8	0.982	1.204	1.287	1.524	1.744	1.513	1.376
14	0.364	1.373	1.532	1.067	1.267	1.201	1.134
20	0.779	1.214	1.771	1.615	1.173	1.690	1.374
21	0.666	0.713	0.707	0.708	0.964	1.174	0.822
22	0.310	0.681	0.721	0.772	0.839	0.626	0.658
23	0.515	0.656	0.691	0.613	0.742	0.544	0.627
24	0.417	0.617	0.796	0.773	0.903	0.583	0.682
25	0.605	0.558	0.481	0.813	1.173	0.576	0.701
Average	0.610	0.860	0.992	1.031	1.125	1.298	0.986
2	0.738	0.892	1.085	0.902	1.499	1.031	1.024
6	0.603	1.025	1.119	0.985	0.876	0.886	0.916
9	0.739	0.963	1.296	1.109	1.174	1.471	1.125
13	1.112	1.299	1.322	0.931	1.643	1.100	1.235
15	0.580	1.079	1.200	0.968	0.832	0.904	0.927
16	0.793	1.225	0.976	0.942	0.730	0.713	0.897
17	0.694	0.747	1.222	1.156	0.833	0.691	0.891
18	0.846	0.937	1.094	0.844	0.796	0.742	0.875
19	0.963	1.586	1.089	1.884	0.921	0.975	1.237
Average	0.785	1.084	1.156	1.080	1.033	0.946	1.014
3	0.726	0.713	0.910	0.853	0.771	0.571	0.757
4	0.717	0.659	0.798	0.712	0.708	0.630	0.704
5	1.031	1.196	1.231	1.064	0.744	0.944	1.035
10	0.676	0.707	0.679	1.521	1.044	0.913	0.923
11	0.558	0.681	0.868	0.692	0.665	0.628	0.682
12	0.809	0.373	1.360	0.764	1.125	0.826	0.960
Average	0.753	0.805	0.974	0.934	0.843	0.752	0.843
Grand Average	0.712	0.900	1.021	0.990	0.985	0.985	0.832

The existence of vertical displacement from the central horizontal plane was tested by "t"-tests between two symmetrical locations (e.g., 10 vs. 12). Significant differences (1 percent probability level) between $\hat{a}_{11}$ values for such locations were found for retort temperatures 243, 279, 297, and 315°F. There were no significant differences indicating asymmetry for the 225 and 261°F. retort temperatures. The significant differences found for the other four temperatures could not be considered as conclusive proof of asymmetry since they indicated for the same temperature simultaneously, both upward and downward shifts, depending on the pair of locations tested. It may be assumed on the basis of experimental evidence that no significant displacement from the central horizontal plane of location of greatest heating lag occurred. These results indicate that the effect of anisotropy of beef has contributed to the displacement of the location of greatest heating lag.

b. Lag coefficient—C_1:

The distribution of lag coefficients (Table 5) followed closely the distribution of intercept coefficients and gave additional evidence of the exist-

TABLE 5

Distribution of lag coefficients (C_i) in 300 x 308 can

r (cm.)	z (cm.) 2.75	2.00	1.00	0.00	−1.00	−2.00	−2.75
				RT = 225°F.			
0	0.694	0.738	0.726	0.717	1.031	0.603	0.734
1	0.982	0.739	0.676	0.558	0.809	1.112	0.364
2	......	0.580	0.793	0.694	0.846	0.963	0.779
3	......	0.666	0.310	0.515'	0.417	0.605	......
				RT = 243°F.			
0	0.861	0.892	0.713	0.658	1.196	1.025	0.720
1	1.204	0.963	0.707	0.681	0.873	1.299	1.373
2	......	1.079	1.225	0.747	0.937	1.588	1.214
3	......	0.713	0.681	0.656	0.617	0.558	......
				RT = 261°F.			
0	0.787	1.085	0.910	0.798	1.231	1.119	0.147
1	1.287	1.296	0.679	0.868	1.360	1.322	1.532
2	......	1.200	0.976	1.222	1.094	1.089	1.771
3	......	0.707	0.721	0.691	7.96	0.481	......
				RT = 279°F.			
0	1.499	0.902	0.853	0.712	1.064	0.985	0.924
1	1.524	1.109	1.521	0.692	0.764	0.931	1.067
2	......	0.968	0.942	1.156	0.844	1.084	1.615
3	......	0.708	0.772	0.613	0.723	0.813	......
				RT = 297°F.			
0	1.494	1.499	0.771	0.707	0.774	0.876	0.954
1	1.073	1.174	1.044	0.665	1.125	1.643	1.267
2	......	0.832	0.730	0.833	0.786	0.921	1.173
3	......	0.964	0.839	0.742	0.903	1.173	......
				RT = 315°F.			
0	3.881	1.031	0.571	0.630	0.944	0.886	1.192
1	1.515	1.471	0.913	0.628	0.826	1.100	1.201
2	......	0.904	0.713	0.691	0.742	0.975	1.690
3	......	0.906	0.702	0.296	1.213	0.423	......

ence of doughnut-shaped volumes of lowest temperatures. It was observed, however, when comparing the values of the coefficients for the central vertical axis with those for the outside vertical axis (D-D) that for retort temperatures from 225-261°F. the outside coefficients were relatively lower than the inside ones. This occurrence indicates a relatively higher contribution of the initial temperature gradient and non-instantaneous retort come-up to the $\hat{a}_{11}$ values compared to the anisotropy effects as discussed previously. In the range of temperatures from 279-315°F. this trend has been partially reversed and the outside lag coefficients were higher than the inside ones indicating a larger contribution of the anisotropy and case-hardening effects for high processing temperatures.

The comparison of the central vertical axis (A-A) with the next closest vertical axis (B-B) indicated on the average the reality of occurrence of cardioid-shaped isothermals especially in the central portion of the container. The lag coefficients for the central axis were lower than the coefficients for the other axes and this trend was more pronounced at higher retort temperatures.

The grouping of the values of intercept coefficients ($\hat{a}_{11}$) and lag coefficients (C_1) by locations (Tables 3 and 5) and by temperatures (Tables 2 and 4) revealed an interesting trend. The coefficients increased in magnitude with the increase in temperature up to the middle of the range tested (225-315°F.) and then decreased; however, for the outside locations the maxima were displaced towards the 297°F. retort temperature. This trend agreed well with the trends displayed by other variables tested during this investigation such as previously discussed displacement of the area of greatest heating lag, and trends for the sterilizing effect and maximum shear force values discussed elsewhere *(3)* as well as for thermal diffusivities and slopes of the heating curves *(3)*, as shown in Tables 6 and 7.

TABLE 6

Slopes ($\hat{b}_{11}$) of heating curves and their variation

RT (°F.)	225	243	261	279	297	315	Average
$b \times 10^3$ (min.)$^{-1}$	23.75	27.29	30.27	29.58	29.62	26.24	27.79
C. V. ($\hat{b}_n$) (%)	7.72	4.57	5.69	5.06	6.02	9.32	6.40
C. V. (RT-CT) (%)	33.16	18.44	21.00	16.79	17.63	11.66	19.78
C. V. (RT-IT) a_{11} (%)	10.96	5.72	7.80	5.51	6.10	4.78	6.81

TABLE 7

Average coefficients and parameters to be used with prediction equation for heating phase and their variation

RT (°F.)	225	243	261	279	297	315	Average
$\hat{K} \times 10^3$ (sq. cm. /min.)	221.63	255.80	281.08	279.46	275.79	259.97	262.29
C. V. ($\hat{K}$) (%)	7.72	4.57	5.69	5.06	6.02	9.32	6.40
C. V. ($\hat{a}_{11}$) (%)	10.46	5.86	6.60	5.47	4.56	3.28	6.37
$C_1 = \hat{a}_{11}/a_{11}$	0.708	0.896	1.020	0.992	0.990	0.896	0.934

c. Experimental errors:

The variation in the determination of the logarithm of the intercept of the heating curve (RT-IT) $\hat{a}_{11}$ (Table 6) did not affect, on the average, more than the second decimal place and thus would result in a ± 7°F. deviation. Taking into account the precision of temperature measurements (± 1°F.) it was rather small. The average coefficient of variation was found to be C. V. = 6.81%. Since each determination was taken from a regression of 9 curves, the coefficient of variation for each curve would be three times larger, which should be kept in mind when an intercept determination is made from one heating curve.

The variation of $\hat{a}_{11}$ was estimated from an approximate formula *(3,* Eq. 3) and the average coefficients of variation $\hat{a}_{11}$ are given in Table 7.

The results of the evaluation of the distribution of $\hat{a}_{11}$ and C_1 give concurrent evidence of the existence of actual temperature distributions different from the theoretically expected. The influence of the possible variation in the rate of heating at different locations in the can has not been taken into account because of the evidence presented by the data on thermal diffusivity and "slopes" of heating curves *(3)*. These data (to be published in Part VI of this series) indicated that no significant differences were observed in the mean values of these properties which would be due to the location in the container.

SUMMARY

Experimental temperature distributions during processing of round of beef in 300-308 cans at 6 retort temperatures ranging from 225-315°F. were determined and found to be in a disagreement with theoretical expectations. The areas of greatest heating lag were found to be displaced from the geometric center of the container and to be located in a doughnut-shaped volume (torus) in the central horizontal section of the can. The form of the isothermal lines was found to be cardioid rather than eliptical in shape.

An analysis was made of causative agents for distorted temperature distributions. The reality of observed temperature distributions was confirmed by an analysis of the distribution of intercept coefficients $[a_{11} = A_{11} J_0 (\mu_1 r) \sin \lambda_1 (z + l)]$ of the heating equation.

On the basis of the results of this investigation it may be concluded that the temperature distributions displaying a doughnut-shaped volume of lowest temperatures in the central horizontal section of the 300 x 308 are a real occurrence caused by anisotropy of beef and non-uniform initial temperature distribution as reflected by the analysis of intercept coefficients in the heating equation.

LITERATURE CITED

1. GILLESPY, T. G. Estimation of sterilizing values of processes as applied to canned foods. I. Packs heating by conduction. *J. Sci. Food Agric.*, **2**, 107 (1951).
2. HICKS, E. W. On the evaluation of canning process. *Food Technol.*, **5**, 134 (1951).
3. HURWICZ, H. Experimental determination and mathematical evaluation of physical characteristics of beef processes at high retort temperatures. (Unpublished Ph.D. thesis, Ames, Iowa, Iowa State College Library, 1953).
4. HURWICZ, H., AND TISCHER, R. G. Heat processing of beef. I. A theoretical consideration of the distribution of temperature with time and in space during processing. *Food Research*, **17**, 380 (1952).
5. HURWICZ, H., AND TISCHER, R. G. Heat processing of beef. II. Development of isothermal and isochronal distributions during heat processing of beef. *Food Research*, **17**, 518 (1952).
6. HURWICZ, H., AND TISCHER, R. G. Heat processing of beef. IV. Functional relationships of temperature, time, and space during processing at high retort temperatures. *Food Research* (this issue).
7. SNEDECOR, G. W. *Statistical Methods.* 1946, The Iowa State College Press, Ames, Iowa.
8. STUMBO, C. R. Bacteriological considerations relating to process evaluation. *Food Technol.*, **2**, 115 (1948).